

Quantum control and semiclassical quantumgravity

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Abstract

Gravity

Three theories in Newtonian limit

Gravity \hat{V}^G : local measurement plus communication

DP: Spontaneous collapse of massive superpositions

[Semiclassical thought-experiment 1986]

[Fragments from history]

[Semiclassical Gravity 1962-63: sharp metric]

[Sharp metric Newtonian limit]

Interaction generated “on phone line”

Quantum control to generate potential (tutorial)

Quantum control to generate potential (summary)

[Decoherent Semiclassical Gravity: unsharp metric]

Unsharp metric Newtonian limit

... coincides with DP wavefunction collapse theory

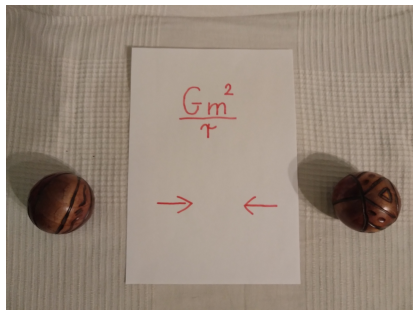
Summary

References

Abstract

Quantum gravity has not yet obtained a usable theory. We apply the semiclassical theory instead, where the space-time remains classical (i.e.: unquantized). However, the hybrid quantum-classical coupling is acausal, violates both the linearity of quantum theory and the Born rule as well. Such anomalies can go away if we modify the standard mean-field coupling, building on the mechanism of quantum measurement and feed-back well-known in, e.g., quantum optics. The newtonian limit can fully be worked out, it leads to the gravity-related spontaneous wave function collapse theory of Penrose and the speaker.

Gravity



MATTER IS QUANTIZED

$\psi(x_1)$

$\psi(x_2)$

NO EXPERIMENTS!
THEORY?

Three theories in Newtonian limit

$$\hat{V}_G = -Gm^2 \times$$

{	$\frac{1}{ \hat{x}_1 - \hat{x}_2 }$	Pair Potential
		no relativistic extension
		Semiclassical Gravity
	$\frac{1}{ \hat{x}_1 - \langle \hat{x}_2 \rangle } + \frac{1}{ \hat{x}_2 - \langle \hat{x}_1 \rangle }$	relativistic (Møller-Rosenfeld 1962-63)
		superluminal, Born rule fails
	$\frac{1}{ \hat{x}_1 - \langle \hat{x}_2 \rangle - \delta x_2 } + \frac{1}{ \hat{x}_2 - \langle \hat{x}_1 \rangle - \delta x_1 }$	Spontaneous Collapse
	↑ stochastic	no relativistic extension
	↑ stochastic	causal, Born rule works

Gravity \hat{V}^G : local measurement plus communication



SPONTANEOUS COLLAPSE (“measurement”)

+

CLASSICAL COMMUNICATION

\Rightarrow

DP THEORY OF SPONTANEOUS WAVEFUNCTION
COLLAPSE

DP: Spontaneous collapse of massive superpositions

D. 1986, Penrose 1996

$$|CAT\rangle = \frac{|\text{LEFT}\rangle + |\text{RIGHT}\rangle}{\sqrt{2}} \rightarrow \begin{cases} |\text{LEFT}\rangle \\ \text{or} \\ |\text{RIGHT}\rangle \end{cases}$$

COLLAPSE RATE: $(V_G^i - V_G^f)/\hbar$

Negligible for atomic masses

Extreme fast for large masses

$\sim 10^9/s$ for 1femtogram, $\sim 10^{19}/s$ for 1gram

**EXPLAINS EMERGENCE OF
CLASSICALITY IN MACROWORLD**

[Semiclassical thought-experiment 1986]

1. electromagnetism
 2. nuclear forces
 3. weak forces
 4. gravity (space-time)
- } quantized, confirmed by tests
unified by the Standard Model
- either quantized or not, no tests so far

Is it sharp or uncertain (fluctuating)?

If it is fluctuating, what is the spectrum of fluctuations δg_{ab} ?

1986: Newtonian limit $\delta g_{00} = \delta\Phi$, thought-experiment with quantized probe + classical Φ , order of magnitude estimate:

$$\langle \delta\Phi_t(\mathbf{r})\delta\Phi_s(\mathbf{y}) \rangle_{\text{stoch}} = \text{const} \times \frac{\hbar G}{|\mathbf{x} - \mathbf{y}|} \delta(t - s)$$

\Rightarrow DP positional decoherence for massive objects, testable in the lab?

Can't we get rid of the order-of-magnitude estimate 1986 ?

2016-17: We can (Tilloy & D).

[Fragments from history]

Bronstein (1935): A **sharp space-time structure is unobservable** (because of Schwarzschild radii of test bodies). Quantization of gravity can not copy quantization of electromagnetism. We may be enforced to reject our ordinary concept of space-time.



1906-1938

Jánossy (1952): Quantum mechanics should be more classical. Expansion of the wave packet might be limited by

$$\dot{\psi}(x) = \frac{i\hbar}{2M}\psi''(x) - \gamma(x - \langle x \rangle)^2\psi(x) + \frac{1}{2}\gamma(\Delta x)^2\psi(x)$$

if we accept **superluminality caused by the non-linear term**.



1912-1978

Károlyházy (1966): The ultimate **unsharpness of space-time structure limits** coherent expansion of **massive objects' position** (while individual particles can expand coherently with no practical limitations).



1929-2012

[Semiclassical Gravity 1962-63: sharp metric]

Sharp classical space-time metric (Møller, Rosenfeld 1962-63):

$$G_{ab} = \frac{8\pi G}{c^4} \langle \Psi | \hat{T}_{ab} | \Psi \rangle$$

Schrödinger equation on background metric g :

$$|\dot{\Psi}\rangle = -\frac{i}{\hbar} \hat{H}[g] |\Psi\rangle$$

That's our powerful effective hybrid dynamics for $(g_{ab}, |\Psi\rangle)$, but

- ▶ with fundamental anomalies (superluminality, no Born rule, ...)
- ▶ that are unrelated to relativity and even gravitation
- ▶ just related to quantum-classical coupling
- ▶ that makes Schrödinger eq. nonlinear

No deterministic hybrid dynamics is correct fundamentally!

Way out: metric cannot be sharp, must have fluctuations δg_{ab} .

[Sharp metric Newtonian limit]

$$G_{00} = 8\pi Gc^{-4} \langle \Psi | \hat{T}_{00} | \Psi \rangle \Rightarrow \Delta\Phi = 4\pi G \langle \Psi | \hat{\rho} | \Psi \rangle$$

$$|\dot{\Psi}\rangle = -(i/\hbar) \hat{H}[g] |\Psi\rangle \Rightarrow |\dot{\Psi}\rangle =$$

$$-(i/\hbar) (\hat{H}_0 + \int \hat{\rho} \Phi dV) |\Psi\rangle \Rightarrow$$

\Rightarrow Schrödinger-Newton Equation with self-attraction:

$$|\dot{\Psi}\rangle = -\frac{i}{\hbar} \left(\hat{H}_0 - G \iint \frac{\hat{\rho}(\mathbf{x}) \langle \Psi | \hat{\rho}(\mathbf{y}) | \Psi \rangle}{|\mathbf{x} - \mathbf{y}|} d\mathbf{x} d\mathbf{y} \right) |\Psi\rangle$$

Single “pointlike” body c.o.m. motion:

$$\dot{\psi}(\mathbf{x}) = \frac{i\hbar}{2M} \nabla^2 \psi(\mathbf{x}) + \underbrace{\frac{i}{\hbar} GM^2 \int \frac{|\psi(\mathbf{y})|^2 d\mathbf{y}}{|\mathbf{x} - \mathbf{y}|}}_{\text{self-attraction}} \psi(\mathbf{x})$$

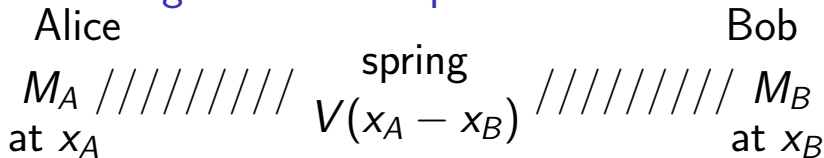
Solitonic solutions: $\Delta x \sim \hbar^2 / GM^3$. self-attraction

Irrelevant for atomic M , grow relevant for nano- M :

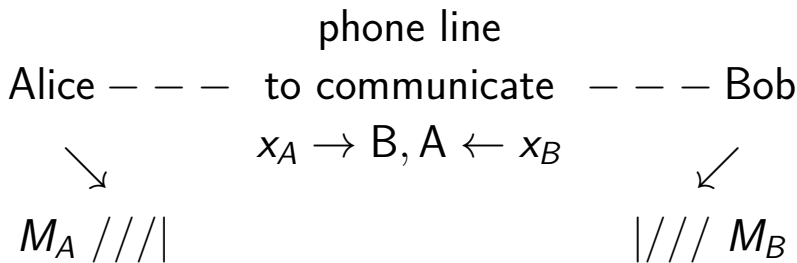
$$M \sim 10^{-15} g, \quad \Delta x \sim 10^{-5} cm$$

That's quantumgravity in the lab [D. 1984].

Interaction generated “on phone line”



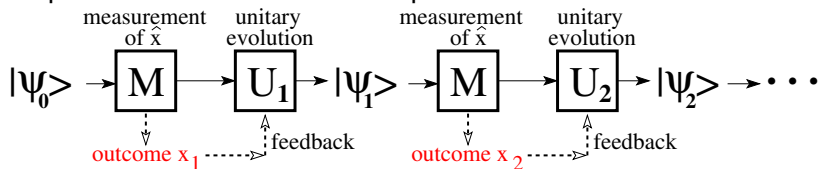
We can replace the spring by a phone line + two local springs under local control of Alice and Bob, resp.:



Trivial classically, **non-trivial in quantum**.
(Kafri, Taylor & Milburn 2014)

Quantum control to generate potential (tutorial)

Sequential measurements of \hat{x} plus feedback:



At ∞ repetition frequency:

standard theory of **time-continuous monitoring+feedback**.

$$\underbrace{x_t}_{\text{signal}} = \underbrace{\langle \Psi_t | \hat{x} | \Psi_t \rangle}_{\text{mean}} + \underbrace{\delta x_t}_{\text{noise}} \quad \underbrace{\mathbb{E} \delta x_t \delta x_s}_{\text{correlation}} = \underbrace{\gamma^{-1}}_{\gamma = \text{precision}} \delta(t - s)$$

To generate a potential, take

$$\hat{H}_{fb}(t) = R x_t \hat{x} = R (\langle \Psi_t | \hat{x} | \Psi_t \rangle + \delta x_t) \hat{x}.$$

$$|\dot{\Psi}\rangle = \frac{-i}{\hbar} (\hat{H}_0 + \underbrace{\frac{1}{2} R \hat{x}^2}_{\text{fb-generated}}) |\Psi\rangle - \frac{1}{8} \underbrace{[\gamma + 4\gamma^{-1} (R/\hbar)^2]}_{\text{to be minimized}} \underbrace{(\hat{x} - \langle \hat{x} \rangle)^2}_{\text{localisation}} |\Psi\rangle + \underbrace{\dots \delta x}_{\text{stochastic}} |\Psi\rangle$$

$$\dot{\hat{\rho}} = \frac{-i}{\hbar} [\hat{H}_0 + \frac{1}{2} R \hat{x}^2, \hat{\rho}] - \frac{1}{2\hbar} R [\hat{x}, [\hat{x}, \hat{\rho}]]$$

Quantum control to generate potential (summary)

Assume \hat{x} is being monitored, yielding signal

$$x_t = \langle \Psi_t | \hat{x} | \Psi_t \rangle + \delta x_t.$$

Apply feedback via the hybrid Hamiltonian

$$\hat{H}_{fb}(t) = R x_t \hat{x} = \underbrace{R \langle \hat{x} \rangle_t \hat{x}}_{\text{sharp semiclassical coupling}} + \underbrace{R \delta x_t \hat{x}}_{\text{(white) noise part of coupling}}$$

Sharp+noisy terms together cancel nonlinearity (and related anomalies) from the quantum dynamics:

$$\dot{\hat{\rho}} = \frac{-i}{\hbar} [\hat{H}_0 + \frac{1}{2} R \hat{x}^2, \hat{\rho}] - \frac{1}{2\hbar} R [\hat{x}, [\hat{x}, \hat{\rho}]]$$

New potential has been generated 'semiclassically' and consistently with quantum mechanics, but at the price of decoherence.

[Decoherent Semiclassical Gravity: unsharp metric]

- ▶ Assume \hat{T}_{ab} is **spontaneously** measured (monitored)
- ▶ Let T_{ab} be the measured value (called **signal** in control theory)
- ▶ Replace Møller-Rosenfeld 1962-63 by

$$G_{ab} = \frac{8\pi G}{c^4} T_{ab} = \frac{8\pi G}{c^4} (\langle \hat{T}_{ab} \rangle + \delta T_{ab})$$

i.e.: source Einstein eq. by the noisy signal
(meanfield+noise)

- ▶ For backaction of monitoring, add terms to Schrödinger eq.:

$$\frac{d}{dt} |\Psi\rangle = -\frac{i}{\hbar} \hat{H}[g] |\Psi\rangle + \text{nonlinear} + \text{stoch. terms}$$

- ▶ Tune precision of monitoring by Principle of Least Decoherence

Unsharp metric Newtonian limit

- ▶ Assume mass density $\hat{\varrho}(\mathbf{x})$ is **spontaneously** measured (monitored)
- ▶ Let $\varrho_t(\mathbf{x})$ be the measured value (called **signal** in control theory)
- ▶ Source classical Newtonian gravity by the signal:

$$\Phi_t(\mathbf{x}) = -G \int \frac{d\mathbf{y}}{|\mathbf{x} - \mathbf{y}|} \varrho_t(\mathbf{y})$$

- ▶ Introduce $\hat{H}_{fb} = \int \hat{\varrho} \Phi dV$ to induce Newton interaction
- ▶ For backaction of monitoring, add standard terms to Schrödinger eq.:

$$\frac{d}{dt} |\Psi\rangle = -\frac{i}{\hbar} (\hat{H}_0 + \hat{H}_{fb}) |\Psi\rangle + \text{nonlinear} + \text{stoch. terms}$$

- ▶ Tune precision of monitoring by Principle of Least Decoherence

Such theory of unsharp semiclassical gravity coincides with ...

... coincides with DP wavefunction collapse theory

Unique ultimate unsharpness of Newton potential Φ (metric):

$$\langle \delta\Phi_t(\mathbf{r})\delta\Phi_s(\mathbf{y}) \rangle_{\text{stoch}} = \frac{\hbar G}{2|\mathbf{x} - \mathbf{y}|} \delta(t - s)$$

By averaging over the stochastic Φ (metric), master eq. (D. 1986):

$$\frac{d\hat{\rho}}{dt} = -\frac{i}{\hbar} \left[\hat{H}_0 - \underbrace{\frac{G}{2} \iint \frac{d\mathbf{x}d\mathbf{y}}{|\mathbf{x} - \mathbf{y}|} \hat{\rho}(\mathbf{x})\hat{\rho}(\mathbf{y})}_{\text{Newton pair potential}}, \hat{\rho} \right] - \underbrace{\frac{G}{2\hbar} \iint \frac{d\mathbf{x}d\mathbf{y}}{|\mathbf{x} - \mathbf{y}|} [\hat{\rho}(\mathbf{x}), [\hat{\rho}(\mathbf{y}), \hat{\rho}]]}_{\text{DP decoherence}}$$

Double merit:

- ▶ **Semiclassical theory of gravity**, a hybrid dynamics of $(\Phi, |\Psi\rangle)$ free of anomalies (no superluminality, valid Born rule).
- ▶ **Theory of G-related spontaneous collapse** (Schrödinger's Cats go collapsed).

Summary

Møller-Rosenfeld (sharp) Semiclassical Gravity is quantum-nonlinear, with related fundamental **anomalies** and particular **effects**:

- ▶ superluminality, fall of Ψ 's statistical interpretation (**anomaly**)
- ▶ self-attraction (**main effect for tests**)

These fundamental anomalies and self-attraction are missing in (unsharp) Decoherent Semiclassical Gravity. But new **anomalies** and **effects** arise:

- ▶ non-conservation of energy, momenta, etc. (**anomaly**)
- ▶ decoherence, c.o.m. Brownian motion, ... (**effects for tests**)
- ▶ submicron cutoff against diverging decoherence (**open problem**)
- ▶ submicron breakdown of Newton force (**effect for tests**)

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